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What's Cool About Hot Stars? Cataclysmic Variables in the Mid-Infrared

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Abstract. We review recent results from mid-infrared observations of cataclysmic variables with the *Spitzer Space Telescope*. In general, these observations have revealed mid-infrared excesses, above the level expected from the stellar and accretion components, in numerous systems. This excess can be modeled as originating from circumstellar and/or circumbinary dust. We present an overview of spectral energy distributions spanning the ultraviolet to the mid-infrared, as well as mid-infrared light curves, of disk-accreting and magnetic cataclysmic variables. Physically realistic models constructed to reproduce these data indicate that the mid-infrared luminosity of many cataclysmic variables is dominated by emission from warm ($T < 2000$ K) dust. The presence and characteristics of dust in cataclysmic variables has potentially important implications for the secular evolution scenario for interacting binary stars.

1. Introduction

Cataclysmic variables are semi-detached binary stars consisting of a white dwarf that accretes matter from a low mass, approximately main sequence secondary star. Cataclysmic variables have typical orbital periods of $P_{\rm orb} < 1$ day. Observational characteristics and types of cataclysmic variables are extensively reviewed by Warner (1995).

Due to its large specific orbital angular momentum, mass lost from the Roche lobe-filling secondary star does not fall directly onto the white dwarf. In most cataclysmic variables, it instead settles into an accretion disk around the white dwarf before losing enough angular momentum through viscous interactions to finally accrete onto the white dwarf. The release of gravitational potential energy in the accretion disk causes it to be, by far, the brightest component of a cataclysmic variable over a wide range of wavelengths. On the other hand, in cataclysmic variables containing a strongly magnetic white dwarf ($B \geq 10$ MG), the matter lost from the secondary star is captured by the field lines and funnelled onto the magnetic pole(s) of the white dwarf. Shocks are created in the accreting material as it impacts onto the pole(s) of the white dwarf, producing emission from X-rays to the optical.

Because of the characteristics of the accretion-generated luminosity, cataclysmic variables have been "traditionally" observed mainly at short wavelengths. Consequently, our understanding of cataclysmic variables has been largely restricted to what can be learned from only the hottest system components, while largely neglecting any cooler components. There is much that can be learned from the observational properties of cataclysmic variables at longer wavelengths.

2. Observations with the *Spitzer Space Telescope*

We have observed a number of cataclysmic variables using the suite of three infrared instruments onboard the *Spitzer Space Telescope*: the Infrared Array Camera (IRAC; Fazio et al. 2004), the Infrared Spectrograph (IRS; Houck et al. 2004), and the Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004). Using observations from these instruments, along with archival and new ground- and space-based observations, we have assembled spectral energy distributions spanning the ultraviolet to the infrared (e.g., see Brinkworth et al. 2007). Using custom-built modeling software, we can explore the contributions to the infrared luminosity in these systems.

In this work, we review our recent results on the short orbital period ($P_{\rm orb} \approx$ 81 min) cataclysmic variables EF Eri (Brinkworth et al. 2007; Hoard et al. 2007) and WZ Sge (Howell et al. 2008), and present new results on the nearly face-on, longer period ($P_{\rm orb} = 166$ min) system V592 Cas. EF Eri is a polar; that is, it contains a highly magnetic white dwarf that prevents the formation of an accretion disk. WZ Sge, on the other hand, does contain an accretion disk and is a so-called Tremendous Outburst Amplitude Dwarf Nova (TOAD; Howell et al. 1995). In both cases, the spectral energy distributions of these cataclysmic variables display an infrared excess that can be reproduced using a simple model for emission from warm ($T < 1000$–2000 K) dust (see Figures 1 and 2).

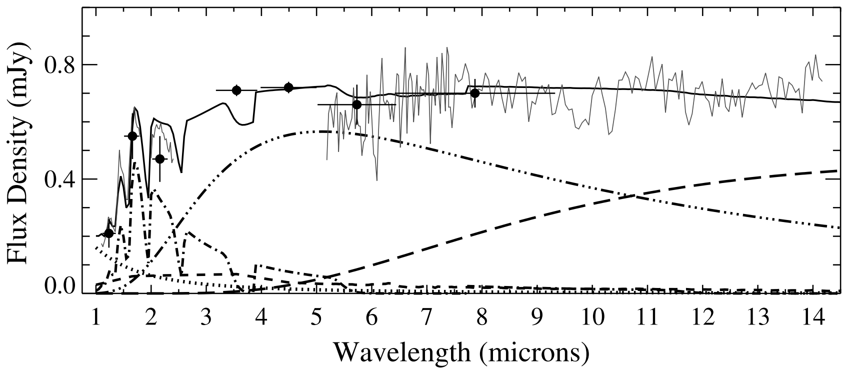

Figure 1. Spectral energy distribution of EF Eri from the ultraviolet to the mid-infrared. Photometric data are shown as points; the x-axis "error bars" show the widths of the photometric bands. Ground-based near-infrared and Spitzer mid-infrared spectra are also shown. The system model (thick solid line) is composed of a 9500 K white dwarf (dotted line), L5 secondary star (short dashed line), cyclotron emission (dot-dash line), and circumbinary dust disk with inner edge temperature of 450 K (long dashed line). The final component (dot-dot-dot-dash line) is a 1000 K blackbody representing emission from a second, warmer dust distribution.

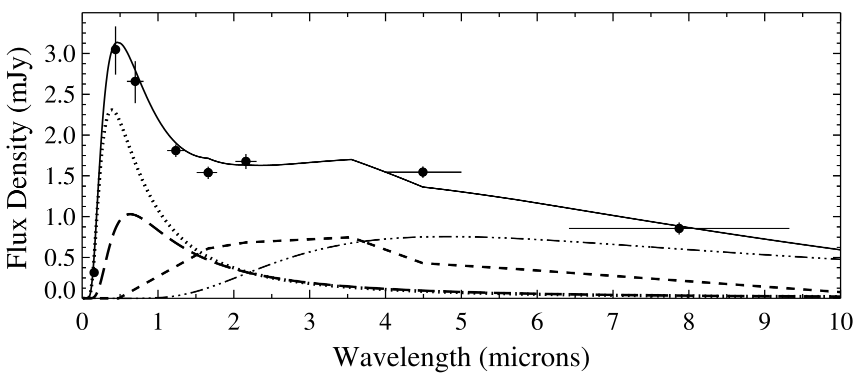

Figure 2. Spectral energy distribution of WZ Sge from the ultraviolet to the mid-infrared. Photometric data are shown as points; the x-axis "error bars" show the widths of the photometric bands. The system model (thick solid line) is composed of a 10,000 K white dwarf (dotted line), L5 secondary star (short dashed line), steady state accretion disk (long dashed line), and circumstellar dust disk around the white dwarf inside the white dwarf Roche lobe with temperature range of 700–1450 K (dot-dot-dot-dash line).

Our *Spitzer* IRAC observations of WZ Sge included the first ever mid-infrared light curve of a cataclysmic variable (see Figure 3). In EF Eri, the large emitting area required to reproduce the observed infrared excess localizes the dust to the circumbinary region. However, in WZ Sge the infrared eclipse is much broader than the optical eclipse, indicating that the dust is *inside* the white dwarf's Roche lobe (infrared emission from circumbinary dust would not display an eclipse). In addition, although the light curves at both 4.5 and 8 μm display some variability outside of eclipse, the ratio of the light curves is flat throughout the orbit of the cataclysmic variable. At the same time, the eclipse depth decreases from 4.5 to 8 μm. Together, these characteristics indicate that the dust distribution has a well-defined low temperature cut-off, which nonetheless occurs at a higher value ($T \approx 700$ K) than the blackbody temperature corresponding to an emission peak at 8 μm ($T_{\rm BB} \approx 350$ K). In the case of a circumbinary disk, there is no obvious mechanism for producing a low temperature cut-off, since the circumbinary disk can, in principle, extend indefinitely until it merges with the local ISM (at $T < 100$ K). However, if the dust is inside the white dwarf's Roche lobe, then the Roche lobe itself defines a strict maximum size (and, hence, minimum temperature) for the dust distribution.

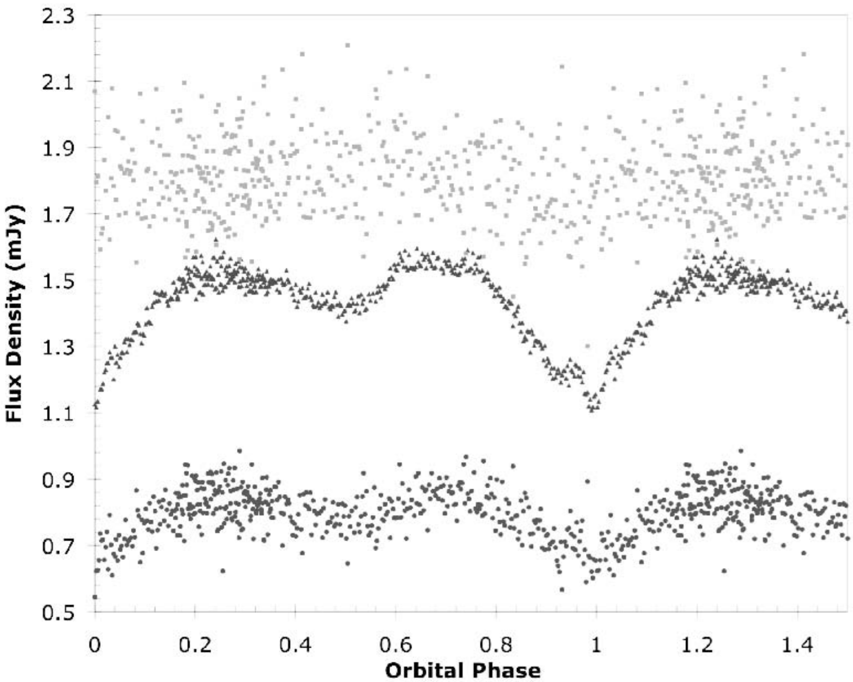

Figure 3. Mid-infrared light curve of WZ Sge from IRAC on the *Spitzer Space Telescope* at 8 μm (bottom), 4.5 μm (middle), and the ratio of the 4.5/8.0 data (top).

Despite the fact that EF Eri and WZ Sge have a significant difference in that the former contains a highly magnetic white dwarf while the latter does not, they still have a number of important structural similarities. For example, they both contain relatively cool ($T \sim 10,000$ K) white dwarfs, and have short orbital periods ($P_{\rm orb} \approx 81$ min), very low mass transfer rates ($\dot{M} \sim 10^{-13}$ $M_\odot$ yr^{-1}), and low mass, brown dwarf-like secondary stars (spectral type L5). In addition, while EF Eri completely lacks an accretion disk, the accretion disk in WZ Sge is very small an does not make a significant contribution in the infrared. Consequently, we examined V592 Cas, which is a longer orbital period ($P_{\rm orb} \approx 166$ min), non-magnetic novalike cataclysmic variable. It has a high mass transfer rate ($\dot{M} \sim 10^{-8}$ $M_\odot$ yr^{-1}; Taylor et al. 1998) and a prominent accretion disk, which is further emphasized by the fact that the system is at a low inclination ($i = 28°$; Huber et al. 1998) so is viewed nearly face-on. In addition, its secondary star is more massive than in the short period systems, with a likely spectral type of M4–5 (Smith & Dhillon 1998; Knigge 2006). Yet, despite all of these factors, which combine to produce a significant infrared contribution (dominated by the accretion disk), the spectral energy distribution still displays an excess at wavelengths longer than 5 μm that can be explained by warm circumbinary dust (see Figure 4).

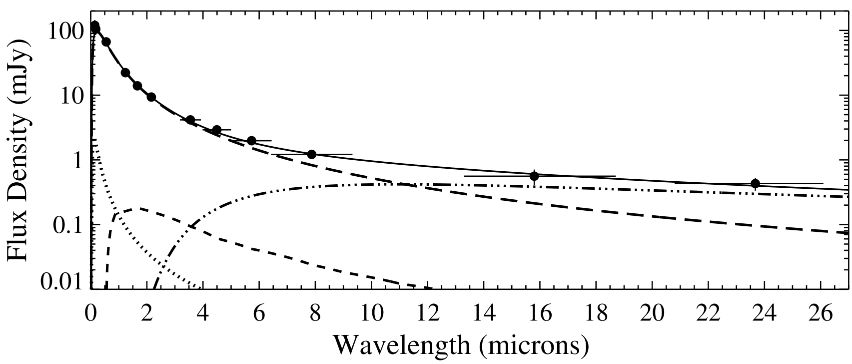

Figure 4. Spectral energy distribution of V592 Cas from the ultraviolet to the mid-infrared. Photometric data are shown as points; the x-axis "error bars" show the widths of the photometric bands. The system model (thick solid line) is composed of a 45,000 K white dwarf (dotted line), M5 secondary star (short dashed line), standard model (Frank, King, & Raine 2002) steady state accretion disk with $\dot{M} = 9 \times 10^{-9}$ $M_\odot$ yr^{-1} (long dashed line), and circumbinary dust disk with inner edge temperature of 760 K (dot-dot-dot-dash line).

3. What Does It All Mean?

Our *Spitzer* infrared observations have shown that dust is apparently a common feature in cataclysmic variables across a wide range of system parameters. The presence of circumbinary dust disks has been suggested as an additional angular momentum loss mechanism driving secular evolution of cataclysmic variables (Spruit & Taam 2001; Taam et al. 2003; Willems et al. 2005, 2007). This could help explain the discrepancies between observations of the population (orbital period) distribution of cataclysmic variables and the standard two-mechanism angular momentum loss model (gravitational radiation and magnetic braking; e.g., see Shafter 1992; Howell et al. 2001). To first order, the standard model can reproduce the general characteristics of the cataclysmic variable orbital period distribution, but it fails in a number of specific details. For example, the standard model would predict a tight relationship between orbital period and mass transfer rate, but there is an observed spread of mass transfer rate at a given orbital period of up to several orders of magnitude (Patterson 1984). In addition, the standard model predicts a minimum cataclysmic variable orbital period (for H-rich systems) of $\approx$ 65–70 min (Patterson 1998; Howell et al. 2001; Willems et al. 2005), which is significantly shorter than the shortest observed orbital periods of $\approx$ 75–85 min (Patterson 1998; Knigge 2006). An additional angular momentum loss mechanism would cause cataclysmic variables to reach their minimum orbital separations faster (i.e., at a longer orbital period).

However, the total modeled mass of dust that we have found in cataclysmic variables so far is many orders of magnitude too small compared to the predicted amount needed to affect cataclysmic variable evolution. The total mass of dust required in our models to reproduce the observed infrared excess is $\sim 10^{18}$–10^{20} g (comparable to the mass of a small asteroid in our solar system), whereas the predicted dust mass required to significantly affect the secular evolution of cataclysmic variables is $\sim 10^{29}$ g. It is possible that the dust masses in cataclysmic variables could initially be higher (e.g., from remnant material deposited during the common envelope phase), and then dissipate over their lifetimes to the low values seen today. However, it is unclear if the corresponding transient additional angular momentum loss produced early in the evolution of the cataclysmic variables could have a significant effect on their characteristics late in life.

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